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The CosmoCube, a didactic cosmic rays portable detector

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Using two plastic scintillator tiles of 12.5 cm x 12.5 cm x 2 cm, we have developed a backpack-size portable cosmic rays detector controlled by a FPGA-based Arduino compatible board. The trigger is selectable between the AND and the OR functions between the two available tiles. In addition to the particle counts, the instrument can measure the time between two consecutive triggers to obtain distributions of the intervals of particle time of arrivals with two timescales, one of them compatible with the muon-decay analysis. Collected data, as well as the instrument configuration, are stored on a non-volatile memory. The collected data can be downloaded at any moment for further analysis. The instrument can be powered through the available USB port by a power bank to allow portable operations. A sound when a cosmic ray passes through the scintillators is generated by the controller that drives also a small LED display to see in real time trigger and tile signals. If necessary, a larger LED display can be connected. Data and status are shown by a LCD display and all can be controlled by three pushbuttons on the front panel. An open version of the instrument can accept up to four scintillators and is used to introduce the basic concepts of coincidence, acceptance, rate, randomness of the events, and allows the students to operate manually themselves the detectors. Additional, analogue output of the signals is available for further didactic purposes. A dedicated PC app can remotely control the instrument for an improved interaction with it.

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1. Introduction

In a world in which young people, in their everyday lives, on the one hand have easy access to the most disparate ideas about the invisible part of reality but on the other hand have mostly lost the personal source of imagination, it is necessary to find a truly engaging and immediate way to arouse interest and wonder about something that cannot be directly touched by hand but only imagined. INFN, in its outreach activity to Italian schools called OCRA[1] (Outreach Cosmic Ray Activity), has decided to use cosmic rays as a topic that can engage children of all ages by making them aware of the existence of invisible "things" that come from the sky and continuously pass through their bodies, objects, buildings and even mountains. It also provides them with "eyes and ears" to "see and hear" the passage of these objects: with the CosmoCube they can experience them directly, as if they see and hear them pass by, and they can make an immediate comparison between what the teacher tells them and what they can directly verify in a few minutes. Since efficient and small detectors are available and electronics allow the use of low-cost programmable integrated components, the detection of secondary cosmic rays can be done in any environment with compact detectors detecting their passage, making real-time measurements of counts, arrival rates and other quantities of physical interest. Such devices easily collect a time statistic and allow the user (the student and teacher) to autonomously set up the detectors to make real-time measurements, fundamental observations, and to have immediate confirmations of phenomena from multiple viewpoints. The device described here, made for this purpose, is named the CosmoCube, name taken from its portable version with two scintillator plates in an almost cubic structure with transparent faces, easily carried in a backpack and immediately operable even by the less experienced via three buttons on the front panel and an LCD display, shown in Fig.1. In its rugged portable version, the CosmoCube measures 19 cm x 19 cm x 22(height) cm and has an approximate weight of 3.6 kg.

There is also an open version of CosmoCube (Fig.2), which is essential for increasing student interaction during outreach events under the expert supervision of an expert.

2. The CosmoCube

In the CosmoCube, the detection of charged secondaries is done by 12.5 cm x 12.5 cm x 2(thickness) cm plastic scintillator tiles. Attached to one side of each scintillator there is a board containing two 6 x 6 mm^2 Silicon PhotoMutipliers (SiPM) from FBK optimized to detect the Near-Ultraviolet light[2] (NUV-HD SiPMs), connected together in parallel to the input of a signal amplifier. A single cable carries the power supply for the amplifier and the bias voltage for the SiPMs as well as the amplified signal to the central unit (Fig.1 right). The individual tile, enclosed in a diffuser material casing, is then enclosed in a slightly larger black box (Fig.1 right), which ensures its light-tightness and safe handling, resulting in a practically independent unit. In the open version it is easily handled in demonstrations by the teacher but also by students who can invent arrangements of the available ones by immediately verifying their detection characteristics. In the closed version, only two tiles are used, placed at a distance of 18 cm. The central unit, which is the same in both versions, consists of a motherboard on which an XLR8-compatible ArduinoUNO processing board[6], which is based on an Intel Max10[4] FPGA, is plugged. Up to four tiles can

Figure 1: The CosmoCube, portable version. On the front panel (left) the display showing the histogram related to muon decay (later discussed), the three buttons for control, the USB port; on the back panel (right) is the audio output, the power connector, the set of LEDs connected to the CosmoCube activity, the connectors for the trigger output and the input for two additional input channels. The top tile (IN0) and the bottom tile(IN1) can be seen.

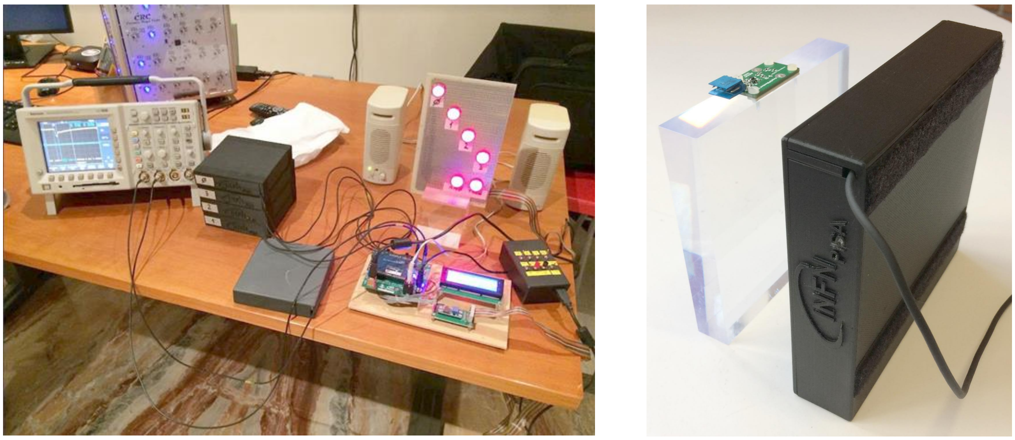

Figure 2: On the left the CosmoCube open version, with oscilloscope and external display, waiting for a meeting with students. On the right the scintillator tile with the sensor board and amplifier, next to the box that contains it.

be managed, and the motherboard has an on-board comparator that provides for the translation of analog signals into digital form that can be read out by the XLR8. On the motherboard, an adjustable step-up voltage converter for biasing the SiPMs, a simple six-LED display (most useful for keeping an eye on operation) and a small transducer that can emit an acustic sound at the arrival of cosmic rays are also present. The Max10, with a custom firmware, uses its internal microprocessor to run the C-based control program and interfaces with the outside world via a USB port. When using the CosmoCube in the close version, the USB port can be used to power it via a simple powerbank. Morever, all functionalities can be controlled from a PC (terminal emulator or appropriate custom developed Graphical User Interface, GUI) via the aforementioned USB port. Instead of a PC, a Raspberry can also be used, for example, which continues to ensure portability and operability of the whole system with powerbank while providing additional wireless connectivity. Additional sensors (inclinometer, GPS, etc.) can be added to the set by connecting them to the Raspberry, maintaining the full transportability of the detector in outdoor excursions. The CosmoCube, in both versions, has a backlit 20x4 LCD display, indipendent from the control board, which allows a view of the main measurements accessible through three screen views: one shows the signal count for each tile, the trigger event count, the measurement of the elapsed time and the average trigger rate, as well as the instantaneous rate calculated in the last 15 seconds; another shows the basic parameters for quick debugging in case of malfunction; finally, the third is dedicated to the display of histograms, a feature better described in section 3. The open version also comes with a keyboard that allows immediate configuration of key parameters (the tiles in use, the type of trigger, ...) keeping teacher and student interaction with the device to the highest levels of flexibility. The teacher can show how to change the configuration during the explanation, nothing hidden and complicated the student then cannot do himself.

In the portable version, students' direct interaction with the detector (even in the absence of a connected PC) is ensured by three buttons that help them quickly make measurements and configurations while taking advantage of the data displayed on the LCD.

3. Measurement of trigger time intervals: muon decay and rate study.

During the development of CosmoCube, we decided to implement an online statistical measure of the time elapsed between consecutive triggers (configurable as AND/OR of the enabled inputs). Analysis of the data thus obtained showed that the corresponding histogram in the first microseconds can be fitted with a decreasing exponential added to flat background. The time constant is compatible with the value of the average muon lifetime. Having made the appropriate verifications with pulse generators and comparisons with what others had obtained with different scintillation detectors[3], we confirmed that we were observing the phenomenon of muon arrest in the detector and subsequent decay of these marked by the signal attributable to the decaying electron. The constant background can be attributed to exponential distribution of consecutive cosmic rate, carachterized by a time constant several order of magnitude larger then the one of the muon decay. We thus implemented in XLR8 an on-line histogram builder, showing on the CosmoCube display the resulting histogram with a bin width of 1 us. The data are stored non-volatile and are downloadable via USB for detailed analysis, here an example of a fit made offline with such data (Fig.3). A further verification was the collection of decay data using two tiles placed between them in AND: the histogram obtained was

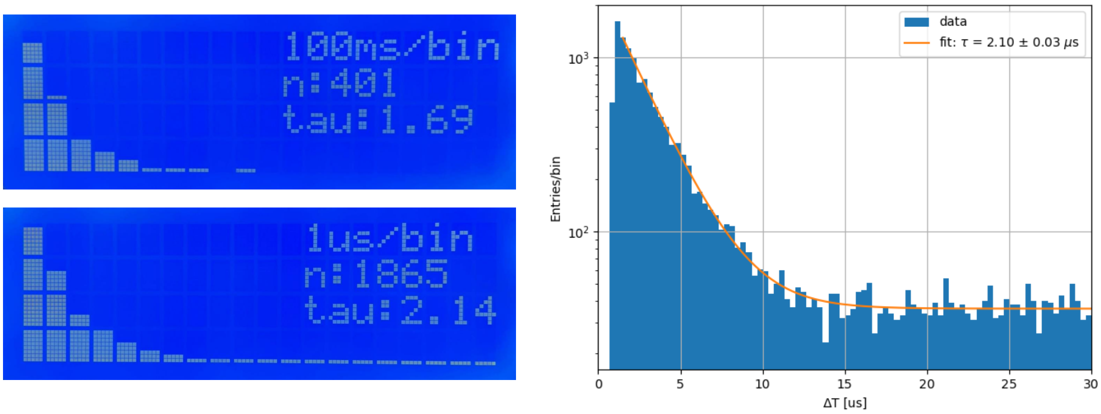

Figure 3: On the left the on-board histogram displays related to muon decay (1 μs/bin, bottom) and particle rate (100 ms/bin, top), with the estimation in bins unit of time constants of the exponential fits. On the right the offline data fit (exp+const.), now integrated in the GUI.

the same, but if a lead absorber is interposed between the two then only the uniform background remains, a sign that the absorber stopped the decay electron that thus could not reach the other tile. The muon decay data are at most 1/1000th of the signals recorded from each tile and thus contribute negligibly to the overall statistics. Thus, if we analyze the above time data on scales up to the second, we still obtain, as expected, a distribution of decreasing exponential but with time constant equal to the rate of the signals. Here, too, we have implemented data storage with the possibility of downloading them via USB, and the construction/display of a histogram with bin equal to 100 ms. While muon decay data take a long time to collect and thus should be well protected against inadvertent deletion, rate data can be used and deleted live to show visually, alternating with numbers, how changing trigger type or detector arrangement quickly generates a different histogram. Directly on the CosmoCube display is an estimate of the time constant of the distribution, histogram and estimate are updated in real time.

4. Interaction with students.

As already mentioned, direct and simple student interaction with the CosmoCube is the aim of the project and was the key aspect of its success during the outreach events and inferable from the questionnaires filled out by the students at their end. Obviously, both the an introductory theoretical seminar and a supervised practical part need to be set up and calibrated to the level of knowledge of the interlocutors (science-based or non-science-based school, age, indications of the accompanying teacher of the students, continuous observation of the reactions of the audience ...). A very attractive aspect turned out to be being able to listen live to the revelation of the passage of particles through the tiles with the strong change from coincidence (AND) to single (OR) mode and vice versa: it is like equipping oneself with special ears to be able to make contact with something invisible; the listener first marvels, then is informed about what he or she is hearing, then is guided to realize the randomness of the phenomenon, being struck by the moments of pause (well emphasized by the teacher) that sometimes make one fear the end of the phenomenon and by the moments of crowded ticking (also well emphasized by the teacher); the very distinct difference in the ticking between the two trigger modes then directly opens the door on the concept of acceptance (Fig.4 left). To keep the attention of the audience even more alive, the hands-on moment is announced several times during the introductory theoretical phase, even before it begins, as a preamble to what is about to be said about a world generally ignored or on which most have never paused to reflect. It is important

Figure 4: Pictures of high school students interacting with the open version of the CosmoCube.

during the theoretical seminar to highlight key points that students can easily test and experiment with on their own by handling the detector tiles and changing the instrument configuration. If there is time to make a quantitative flow measurement, it is good, for example, to involve all the children in counting while one of them takes the time, rather than relying on the numbers on the display. Students are impressed to know that the muons that reach us also pass through their bodies (Fig.4 right) and generally want to check that it is true by putting their hands and heads between two tiles. The teacher urges them to check, puts doubt in their minds that it is true. The possibility of being able to have the CosmoCube in their schools for a period of time, using it independently after a very short teacher training, makes it a winning element to extend their curiosity about the topic beyond the few hours officially dedicated to the outreach event. We put here photos taken during the practical part of some meetings in which the kids interaction with the instrument can be seen.

5. Possibility of measurements.

As mentioned above, the resident firmware/software automatically performs counts for each tile's signals, elapsed time, trigger events and also performs calculation of the average trigger rate and "instantaneous" rate over the last 15 seconds to highlight the variability of the flow. The program on a PC via a Python-based GUI makes these functions available as well as plots the counts and rate as a function of time. As an example, in Fig.5 (top left) is a time record of the rate of a tile placed on the table alternately horizontally and vertically: the change in relative rate and a downward trend in absolute flux during the approximately six hours of the observation is clearly visible. Another example of the potential of the GUI is the ability to extract the data stored in the CosmoCube and make a histogram with relative fit (Fig.5 right). Flow measurements can be made at various inclinations, at various altitudes, at various floors of a building, in underground areas (caves, tunnels, ...). It only takes a few minutes to get significant numbers. In 2022, a version of the

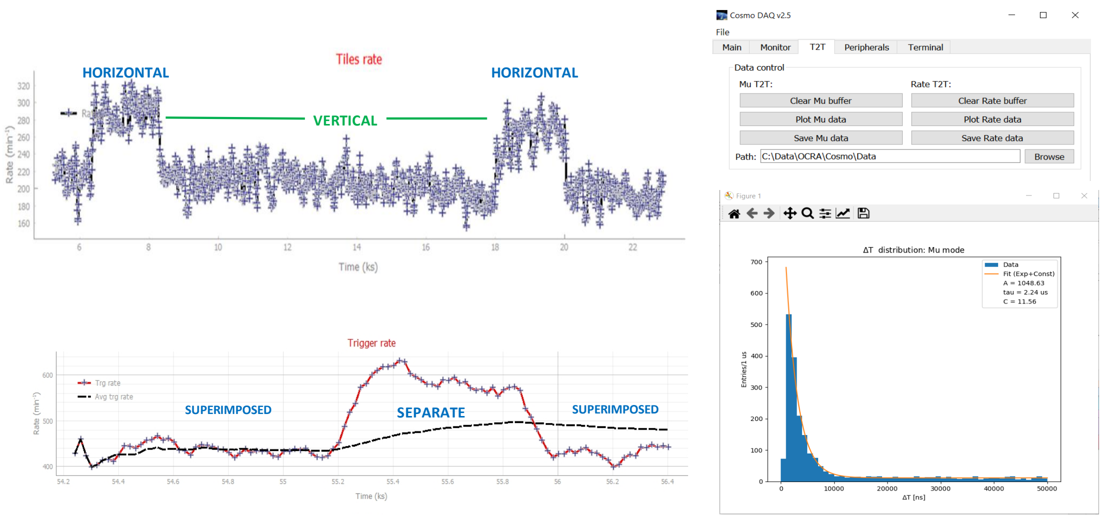

Figure 5: On the left examples of the rate trends shown in the GUI, on top the trigger rate of a single tile when placed vertically or horizontally, on the bottom the trigger rate of the OR of two tiles when superimposed or displaced (rate depends on the plane surface covered). On the right the GUI panel to generate/save/clear the histograms of the time intervals, with an example of a plot automatically generated).

CosmoCube equipped with Raspberry for recording data every second, with three tiles arranged in a studied way to measure horizontal and vertical flow simultaneously, was placed aboard a balloon that reached the altitude of more than 32 thousand meters confirming the variation of flow with the altitude well known in the literature. The counts for the single tile reached 170 Hz at about 20 km altitude versus a few Hz on the ground. The horizontal flux increased to about 23 km then stabilized to the maximum altitude[7]. The use of offline histograms (muon decay and rate measurement) is reserved for more advanced students. It is a topic of the annual editions of ICD (International Cosmic Day). Likewise are the observation of signals at the oscilloscope (possible for two tiles with the open version) and the issue of the on-board comparator threshold related to the use of two SiPMs in parallel rather than one. In a longer run, it may be interesting either to devote oneself to taking data concerning muon decay (the "strange" populating of the histogram visible in a few hours, a fit possible after a few days), or to obtaining in a few hours the Rossi Curve[5] using the 4 tiles of the open version. In general, it is possible to observe extensive cosmic swarms if one has several open systems in connection with each other so as to cover a relatively large area. It is also possible to observe the variability of the flow throughout the day and under different weather conditions. The motherboard is equipped with Lemo connectors for displaying signals from two tiles to the oscilloscope, making it possible to measure the time distance between the two. The tiles can be placed vertically at each other up to two meters apart. Observation of the two signals in temporal coincidence shows that the top tile is crossed first in each case, even if the exchange is made, and the thus calculable velocity of the particle is close to that of light. Then there is a whole series of observations related to the rate measured by the single tile placed on top or under another tile, placed horizontally or vertically, of the concept of detector acceptance: a training ground for the student's mind that makes predictions, tries to verify them, takes note of phenomena and tries to explain them.

6. Conclusions

The CosmoCube has proven to be an excellent tool for educational purposes. The small size combined with its low power consumption, the ability to make significant flux measurements in a few minutes, the possibility of direct interaction with the student who can handle the detectors and intuitively modify the basic functionality of the instrument on the fly without the use of a PC, and the listening that bystanders can do of the particle passage, has captured the interest of the participants and especially of those who have operated it at every meeting. Control, monitor data export and analysis is possible through an user friendly GUI. With the open version, interesting measurements and observations can be made in a more in-depth laboratory activity. Without making any modifications, other types of detectors having negative signals of a few volts maximum and a duration of a few hundred ns can be connected to the CosmoCube. For other types of signals, both hardware and firmware may need to be modified. First tests of coincidence of multiple CosmoCubes have recently been carried out successfully, opening the door to measurement of swarms with detectors placed at a relatively large distance.

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